

**OPTICAL RECEIVERS**

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**Abstract**

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An optical receiver includes a reverse biased photodiode (10) whose output is coupled to a transimpedance amplifier (13). A load impedance for the photodiode can comprise a forward biased semiconductor diode (20), enabling the photodiode to be biased using a low voltage supply (V+). A signal compressing arrangement (25-27) can be provided between the transimpedance amplifier output and the semiconductor diode (20). The transimpedance amplifier (13) can have a capacitive transimpedance element (28) to provide an integrating response; a filter (44), including an open circuit transmission line (40), is described which is coupled to the output of such an optical receiver (42) to provide a desirable form of optical receiver arrangement. The capacitive transimpedance element can be constituted by a capacitance of the photodiode (10).

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<b>(21) International Application Number:</b> PCT/CA90/00117 <b>(22) International Filing Date:</b> 11 April 1990 (11.04.90) <b>(30) Priority data:</b> 596,657 13 April 1989 (13.04.89) CA <b>(60) Parent Application or Grant</b> <b>(63) Related by Continuation</b> US 337,810 (CIP) Filed on 14 April 1989 (14.04.89) <b>(71) Applicant (for all designated States except US):</b> NORTHERN TELECOM LIMITED [CA/CA]; 600 de la Gauchetière Street West, Montreal, Quebec H3B 4N7 (CA).		<b>(72) Inventor; and</b> <b>(75) Inventor/Applicant (for US only):</b> KAHN, David, Alexander [CA/CA]; 3 Wareham Street, Nepean, Ontario K2H 6P7 (CA). <b>(74) Agent:</b> SMITH, Dallas, F.; Northern Telecom Limited, Patent Department, P.O. Box 3511, Station C, Ottawa, Ontario K1Y 4H7 (CA). <b>(81) Designated States:</b> AT (European patent), BE (European patent), CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent), US. Published With international search report.
<b>(54) Title:</b> OPTICAL RECEIVERS <div style="text-align: center; margin: 20px;"> </div> <p><b>(57) Abstract</b></p> <p>An optical receiver includes a reverse biased photodiode (10) whose output is coupled to a transimpedance amplifier (13). A load impedance for the photodiode can comprise a forward biased semiconductor diode (20), enabling the photodiode to be biased using a low voltage supply (V+). A signal compressing arrangement (25-27) can be provided between the transimpedance amplifier output and the semiconductor diode (20). The transimpedance amplifier (13) can have a capacitive transimpedance element (28) to provide an integrating response; a filter (44), including an open circuit transmission line (40), is described which is coupled to the output of such an optical receiver (42) to provide a desirable form of optical receiver arrangement. The capacitive transimpedance element can be constituted by a capacitance of the photodiode (10).</p>		

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OPTICAL RECEIVERS

This invention relates to optical receivers, and is particularly concerned with an optical receiver including a photodiode and a transimpedance amplifier.

5 It is known from an article entitled "Atlanta Fiber System Experiment: Optical Detector Package" by R.G. Smith et al. in the Bell System Technical Journal, Vol. 57, No. 6, July-August 1978, pages 1809 to 1822 to provide an optical receiver comprising an avalanche photodiode (APD) coupled to a transimpedance amplifier. The  
10 transimpedance amplifier is a shunt feedback amplifier which acts as a current-to-voltage transducer providing an output voltage determined by the photodiode current multiplied by the feedback resistance. It has the advantages of being less noisy for a given bandwidth than an unequalized amplifier which does not employ feedback, and having a  
15 larger dynamic range than, and not requiring individual adjustment as does, an equalized amplifier.

It is also known from an article entitled "Detectors - Inexpensive p-i-n photodiodes match fiber, source characteristics" by P.H. Wentland et al. in Electronics, August 5, 1976, pages 101 and 102  
20 to provide an optical receiver comprising a high performance p-i-n type silicon photodiode coupled to a transimpedance amplifier.

A problem with such known optical receivers is that the photodiode is reverse biased via a load resistor which must have a relatively high resistance in order to minimize noise. This  
25 resistance, in conjunction with the reverse bias supply voltage, limits the upper level of photocurrent which can be accommodated, and hence limits the dynamic range of the optical receiver. There is thus a direct conflict between the desire for a high resistance to minimize noise and a low resistance to maximize dynamic range. Typically, a  
30 relatively high resistance has been used in conjunction with a relatively high voltage power supply to increase the upper limit of photodiode current. It would be desirable to eliminate the need for such a high voltage power supply, and to reverse bias the photodiode from the same power supply, typically having a low voltage of 5 volts,  
35 as is used for other parts of an optical receiver arrangement. In addition, it is desirable to use most of the supply voltage for

reverse biasing the photodiode and thereby reducing its capacitance and improving its speed and noise characteristics.

An object of this invention, therefore, is to provide an improved optical receiver.

- 5 According to one aspect of this invention there is provided an optical receiver comprising: a transimpedance amplifier comprising an amplifier having an inverting input, an output, and a transimpedance element coupled therebetween; a photodiode and a d.c. load impedance therefor connected in series therewith; means for  
10 reverse biasing the photodiode via the d.c. load impedance; and coupling means coupling a junction between the photodiode and the d.c. load impedance to said inverting input; characterized in that the d.c. load impedance comprises a forward biased semiconductor diode.

- In such an optical receiver, the forward biased semiconductor  
15 diode provides a desirable load impedance for the reverse biased photodiode, without necessitating a large voltage drop at high photocurrent levels and without significantly affecting noise and dynamic range characteristics. The relatively low forward voltage drop across this semiconductor diode enables low supply voltage  
20 levels, of the order of 5 volts, to be used for biasing the combination of the photodiode and load impedance.

- In an embodiment of this aspect of the invention, the transimpedance element comprises a capacitance. The transimpedance amplifier consequently contributes little noise, especially if it is  
25 an a.c. coupled amplifier with its input connected directly, i.e. without a coupling capacitor, to the photodiode. Such a transimpedance amplifier acts as an integrator, having a gain which decreases, with increasing frequency, at a rate of 6dB/octave. Accordingly, the optical receiver preferably also includes filtering  
30 means having an input coupled to the output of the transimpedance amplifier and having a compensating frequency-dependent gain, which increases at a rate of 6dB/octave with increasing frequency.

- According to another aspect of this invention there is provided an optical receiver comprising: a transimpedance amplifier comprising  
35 an amplifier having an inverting input, an output, and a transimpedance element coupled therebetween; a photodiode and a d.c.

load impedance therefor connected in series therewith; means for reverse biasing the photodiode via the d.c. load impedance; and coupling means coupling a junction between the photodiode and the d.c. load impedance to said inverting input; characterized in that the  
5 transimpedance element is capacitive.

The invention will be further understood from the following description with reference to the accompanying drawings, in which similar references are used throughout the different figures to denote similar components, and in which:

10 Figs. 1 and 2 schematically illustrate known optical receivers each including a photodiode and a transimpedance amplifier;

Fig. 3 schematically illustrates an optical receiver, including a photodiode and a transimpedance amplifier, in accordance with an embodiment of this invention;

15 Fig. 4 schematically illustrates a form of transimpedance amplifier which may be used in an optical receiver in accordance with this invention;

Figs. 5 to 8 schematically illustrate optical receivers in accordance with other embodiments of this invention;

20 Figs. 9 to 11 schematically illustrate alternative forms of a filter particularly suited for use in an optical receiver arrangement including the optical receiver of Fig. 6, 7, or 8;

Fig. 12 illustrates in a block diagram an optical receiver arrangement including the optical receiver of Fig. 6, 7, or 8 and the  
25 filter of Fig. 9, 10, or 11;

Figs. 13 and 14 schematically illustrate optical receivers in accordance with other embodiments of this invention;

Fig. 15 schematically illustrates a compensating circuit for use with the optical receiver of Fig. 14; and

30 Fig. 16 illustrates in a block diagram an optical receiver arrangement including the optical receiver of Fig. 14, the compensating circuit of Fig. 15, and the filter of Fig. 9, 10, or 11.

Referring to Fig. 1, there is illustrated a known form of optical receiver which comprises a photodiode 10 which is directly  
35 coupled to a transimpedance amplifier comprising an inverting amplifier 12 and a transimpedance resistor 14. The photodiode 10 is for example an avalanche photodiode or p-i-n type silicon photodiode

which serves to receive a modulated light signal, as represented by arrows, for example from an optical fiber (not shown) of a communications system. In this direct-coupled optical receiver, the photodiode 10 is reverse biased by a power supply voltage  $V_+$ , and the transimpedance amplifier produces an output signal voltage  $V_o$  representing the modulation signal. The transimpedance resistor 14 has a relatively high resistance and serves as a load resistor for the photodiode 10.

Fig. 2 shows an a.c. coupled optical receiver which similarly includes a photodiode 10 and a transimpedance amplifier comprising an inverting amplifier 12 and a transimpedance resistor 14. In the optical receiver of Fig. 2, the photodiode 10 is coupled to a negative supply voltage  $V_-$  via a resistor 16 which serves as a load resistor for the photodiode 10, and the junction between the photodiode 10 and its load resistor 16 is a.c. coupled to the input of the transimpedance amplifier by a coupling capacitor 18.

As discussed in the introduction above, in order to provide desirable noise characteristics the load resistor for the photodiode 10, namely the resistor 14 in the optical receiver of Fig. 1 and the resistor 16 in the optical receiver of Fig. 2, must have a high resistance. Consequently, one or both of the power supply voltages  $V_+$  and  $V_-$  has a relatively large magnitude, of for example 15 volts or more. Accordingly, such supply voltages must be provided specifically for biasing the photodiode 10, even though much lower supply voltages, of for example 5 volts, are typically used for powering the amplifier 12 and subsequent digital circuitry which is provided for processing the output signal  $V_o$  of the optical receiver.

Fig. 3 illustrates an optical receiver in accordance with an embodiment of this invention which enables this disadvantage of the prior art to be avoided. In the optical receiver of Fig. 3, the photodiode 10 is directly coupled to the transimpedance amplifier comprising an a.c. coupled amplifier 13 and transimpedance resistor 14, the transimpedance resistor 14 being a.c. coupled to the output of the amplifier 13 via a coupling capacitor 15. In contrast to the prior art, in the optical receiver of Fig. 3 the photodiode 10 is reverse biased via a forward biased diode 20, which constitutes a d.c. load impedance for the photodiode. The diode 20 desirably has a

small junction area to minimize its capacitance, and maximize its a.c. impedance, particularly at low bias levels, and should have a low reverse leakage. For example, the diode 20 may be a silicon diode type 1N914. Alternatively, and especially for high speed

5 applications, the diode 20 may be a p-i-n type diode having a low capacitance, for example Hewlett-Packard type 5082-3900.

The a.c. coupled amplifier 13 conveniently has a form such as that described below with reference to Fig. 4. A d.c. coupled amplifier, such as the amplifier 12 of the prior art, could be used in  
10 the optical receiver of Fig. 3 with a.c. coupling of the junction between the diodes 10 and 20 to the input of the transimpedance amplifier, for example via the capacitor 18. However, the direct coupling of Fig. 3 is preferred because it can be physically smaller than a.c. coupling. This is significant because the virtual-ground  
15 input of the transimpedance amplifier is very sensitive to electro-magnetic interference, and because any stray capacitance results in extra noise.

Referring to Fig. 4, the a.c. coupled amplifier 13 conveniently comprises an input field effect transistor 21, connected in common-drain or source-follower mode, and a bipolar transistor 22 connected  
20 in common-emitter mode, with a.c. coupling therebetween via a capacitor 23. Resistors connected between the collector-base and base-emitter electrodes of the transistor 22 have high resistances which are selected to bias the amplifier output at about mid-way  
25 between the 0V and 5V supply rails.

Referring again to Fig. 3, in the presence of an incoming modulated light signal, the photodiode 10 generates a photocurrent which flows through the diode 20, which acts as a d.c. load impedance for the photodiode 10. The diode 20 has a small-signal resistance  
30 which is inversely proportional to the photocurrent, and the transimpedance amplifier is designed to have a much lower input impedance than this small-signal resistance. Consequently, substantially all of the modulated signal current is coupled to the input of the transimpedance amplifier, and flows to the transimpedance  
35 resistor 14, rather than being lost in the load diode 20.

The load diode 20 contributes noise which is thermal noise associated with the diode's small-signal resistance. For a silicon



diode 20 such as that referred to above, having an ideality factor of about 2, the mean square current noise is approximately equal to the quantum shot noise associated with the photocurrent. Consequently, the noise increase due to the presence of the load diode 20 is relatively small, and the total noise present at the input of the transimpedance amplifier is typically insignificant in comparison to the thermal noise of the amplifier itself.

In contrast to the prior art, in the optical receiver of Fig. 3 the direct voltage which is dropped across the load impedance for the photodiode 10, namely the diode 20, is limited to about 0.7 volt even at the highest common photocurrent levels. In consequence, the potential difference between the supply voltages  $V_+$  and  $V_-$  can be greatly reduced, to the order of 5 volts. This advantage is achieved without compromising the dynamic range or noise levels of the optical receiver.

As in the prior art, the photodiode 10 in the optical receiver of Fig. 3 may be an avalanche photodiode especially for high frequency modulating signals of the order of 600Mb/s or more, or may be a p-i-n type photodiode, especially for these or lower frequency modulating signals.

As is well known, the resistance of the transimpedance resistor 14 should be high in order to achieve a high gain and low noise. However, the supply voltage for the amplifier 13 must exceed, with some margin, the product of peak-to-peak photocurrent with the transimpedance resistance. For optimal results, typically the quiescent bias level of the output of the amplifier 13 is designed, as described above in relation to Fig. 4, to be close to the midpoint between the power supply voltages  $V_+$  and  $V_-$ . As the signal level increases, it appears symmetrically about this bias level, the coupling being a.c.

With binary digital modulating signals, a linear amplifier characteristic is not essential, and signal compression is possible. It is known to achieve such signal compression by providing a pair of semiconductor diodes connected in parallel with one another and with opposing polarities, in parallel with the transimpedance resistor 14. However, the capacitance associated with such diodes causes a frequency and level-dependent distortion of the signal to a degree

which may be unacceptable. In particular, where the transimpedance resistor has a high resistance, for example  $1\text{M}\Omega$ , the capacitance of the diodes degrades the frequency response of the optical receiver at low signal levels.

5        Fig. 5 illustrates an optical receiver which provides signal compression but which avoids this disadvantage. In the optical receiver of Fig. 5, an impedance 24, for example comprising a  $1\text{k}\Omega$  resistor and a  $1\text{nF}$  capacitor in parallel with one another, is connected between the load diode 20 and the negative supply voltage  
10     $V_-$ . The relatively small resistance of the impedance 24 is such that the voltage drop across this resistor is much less than 1 volt even at the highest photocurrent levels. In this optical receiver, signal compression is provided by a pair of oppositely poled diodes 25 and 26, connected in parallel with one another, a.c. coupled via a  
15    capacitor 27 between the output of the amplifier 13 and the junction between the load diode 20 and the impedance 24.

At low signal levels, the signal compression diodes 25 and 26 are substantially capacitive, but they are isolated from the input node of the transimpedance amplifier by the load diode 20, which has a  
20    relatively high impedance at low signal levels. In addition, the impedance 24 forms with the signal compression diodes 25 and 26 a potential divider, which due to the low magnitude of the impedance 24 greatly attenuates the level of the output voltage  $V_o$  which is fed back towards the input of the transimpedance amplifier. Consequently,  
25    the optical receiver of Fig. 5 avoids the capacitive feedback problems of the known signal compression arrangements discussed above.

At high signal levels, at which the load diode 20 has a relatively low impedance, the output voltage  $V_o$  drives the diodes 25 and 26 into conduction at the instantaneous extreme signal levels, and  
30    current flows back into the virtual ground at the input node of the transimpedance amplifier via the diode 20. The optical receiver thus provides a considerable dynamic range. With a potential difference of 5 volts between the supply voltages  $V_+$  and  $V_-$ , the compressed output signal level  $V_o$  is typically of the order of 0.5 volt peak-to-peak.

35        Fig. 6 illustrates a further form of optical receiver which is similar to that of Fig. 3, except that the transimpedance resistor 14 and coupling capacitor 15 are replaced by a capacitor 28. The

capacitor 28 has a capacitance which is small in relation to the capacitance of the photodiode 10 and the input capacitance of the amplifier 13 in order not significantly to degrade the noise performance of the optical receiver, especially at high frequencies.

- 5 Assuming that the amplifier 13 has a conventional single pole open loop characteristic, the input impedance of the transimpedance amplifier with the capacitive feedback provided by the capacitor 28 is resistive. As indicated above, this input impedance is designed to be much less than the small-signal resistance of the load diode 20.

- 10 As the transimpedance amplifier in the optical receiver of Fig. 6 has only capacitive feedback, the feedback element generates no noise. The resistive noise contribution, which is typically dominant, of conventional transimpedance amplifiers having resistive feedback is thereby avoided, resulting in improved sensitivity of the optical  
15 receiver. In addition, a transimpedance amplifier having capacitive feedback as shown in Fig. 6 is relatively stable and can be relatively easily manufactured.

The capacitor 28 can typically have a capacitance which is less than 1pF, enabling the transimpedance amplifier to have a high gain.

- 20 This gain is frequency dependent, rolling off linearly with increasing frequency, at a rate of 6dB/octave. If a flat response is desired, the optical receiver output signal voltage  $V_o$  can be coupled via an equalization stage, such as a differentiator, having a frequency dependent gain. However, such an equalization stage is unnecessary in  
25 an optical receiver arrangement as described below with reference to Fig. 12.

Instead of providing the capacitor 28 as a transimpedance element, the capacitance of the photodiode 10 itself may be used by connecting the photodiode 10 in the feedback path of the amplifier 13.

- 30 Figs. 7 and 8 illustrate optical receivers in which this is done.

- Referring to Fig. 7, the photodiode 10, reverse biased from a -5 volt supply via the forward biased diode 20, is a.c. coupled in the feedback path of the amplifier 13 by the coupling capacitor 15 and a potential divider constituted by resistors 30 and 31, the photodiode  
35 10, resistor 30, and capacitor 15 being connected in series between the inverting input and the output of the amplifier 13, and the

resistor 31 being connected between a zero volt supply line and the junction between the photodiode 10 and the resistor 30.

The capacitor 15 serves to block d.c., and has a capacitance which is very much greater than that of the photodiode 10. The  
5 potential divider attenuates the output of the amplifier 13 by a factor of for example about 5 determined by the ratio of the resistances of the resistors 30 and 31 (for example 500 and 100 ohms respectively); whereby the effective capacitance of the transimpedance circuit is equal to the capacitance of the photodiode 10 divided by  
10 this factor. The attenuator thus avoids too high an effective capacitance in the feedback path, and hence too low a gain of the transimpedance amplifier. With a low capacitance of the photodiode 10 it is conceivable that the attenuator (resistors 30 and 31) could be omitted.

15 In the optical receiver of Fig. 7, the resistors 30 and 31 introduce a noise component which is undesirable. This is avoided by the alternative arrangement of Fig. 8, in which the attenuator is formed by a capacitive potential divider comprising capacitors 30' and 31'. The capacitors 30' and 31' can have capacitances of for example  
20 10pF and 50pF respectively, to provide the same attenuation factor of about 5 as in the optical receiver of Fig. 7. In view of this capacitive coupling, in the optical receiver of Fig. 8 the coupling capacitor 15 of Fig. 7 is not required, but a resistor 29 is provided in parallel with the capacitor 31' to provide a d.c. path for the  
25 photodiode 10. The resistor 29 is selected to have a resistance which is high compared with the impedance of the capacitor 31' which shunts it, whereby its noise contribution is also shunted and thereby reduced, but which is not so high that it overly restricts the dynamic range of the optical receiver.

30 The same comments, regarding the frequency dependence of gain, apply to the optical receivers of Figs. 7 and 8 as to the optical receiver of Fig. 6, because these optical receivers also have a capacitive transimpedance element.

In an optical receiver arrangement, the output signal from an  
35 optical receiver is typically coupled via a filter which is designed to maximize the "eye" opening while minimizing noise by restricting bandwidth. Such a filter desirably is a matched filter having a sinc

((sine x)/x) response, augmented by a low-pass filter for removing noise from second and subsequent lobes of the sinc filter. Fig. 9 illustrates a sine filter which is particularly suited for such purposes when used with the optical receiver of Fig. 6, 7, or 8.

5 Referring to Fig. 9, the filter illustrated therein comprises an NPN bipolar transistor 32, having a base for receiving an input voltage  $V_{in}$ , a collector for supplying an output signal voltage  $V_{out}$ , coupled to a positive supply voltage of 5 volts via a collector resistor 34, and an emitter coupled via resistors 36 and 38 to a zero  
10 voltage supply rail. In addition, the filter comprises an open circuit transmission line 40, one end of which is coupled across the resistor 38. The transmission line 40 may comprise a coaxial cable, stripline, or any other form of transmission line suitable for providing a delay as described below. The resistor 36 couples the  
15 emitter of the transistor 32 to the transmission line 40 in a matched manner. To this end the resistance of the resistor 36, plus the output impedance at the emitter of the transistor 32, in parallel with the typically much greater resistance of the resistor 38, is selected to equal the characteristic impedance of the transmission line 40, for  
20 example 50 ohms. For example, the output impedance of the transistor may be of the order of 10 ohms, and the resistors 36 and 38 may have resistances of the order of 40 ohms and 1000 ohms respectively. The resistor 34 may conveniently have a resistance of the order of 50 ohms.

25 The transmission line 40 is selected to have a length which is such that the signal propagation delay along the transmission line from its connected end to its open circuit end is equal to half the bit period  $T$  of a binary digital signal to be filtered, whereby the round-trip transmission delay along the line 40 and back is equal to  
30 the bit period  $T$ . For a signal with a bit rate of 600 Megabits per second the length of the transmission line 40 would be typically about 17 centimeters. A signal appearing in the emitter circuit of the transistor 32 is reflected by the open circuit end of the transmission line 40, whereby the filter provides a sine  $(\omega T/2)$  response.

35 Fig. 10 illustrates an alternative form of sine filter, which is similar to that of Fig. 9 except that the resistor 38 is dispensed with, and a constant current circuit 39 is connected between the

emitter of the transistor 32 and the zero volt supply line. Again in this case, the resistor 36 provides a matched coupling of the emitter of the transistor 32 to the line 40.

Fig. 11 illustrates a further alternative form of sine filter which is at present preferred. The filter of Fig. 11 substitutes the resistor 38 for the constant current source 39 of the filter of Fig. 10, and provides a differential output voltage  $V_o$  taken from the collector of the transistor 32 with respect to the collector of another transistor 32', whose base is supplied with the input signal  $V_{in}$  and which has collector and emitter resistors 34' and 38', but no transmission line associated therewith. The differential output and the components 32', 34', and 38' serve to eliminate from the output voltage  $V_o$  effects arising from the resistor 38 and any capacitance at the emitters of the transistors.

As explained above, the optimum filter has a sinc response of the form  $(\text{sine } (\omega T/2))/(\omega T/2)$ , which can be achieved by cascading the sine filter of Fig. 9, 10, or 11 with an integrating stage which supplies the inverse frequency dependent response of  $2/\omega T$ . However, the optical receiver of Fig. 6, 7, or 8 already provides such an integrating function, so that the circuits of Fig. 6, 7, or 8 and Fig. 9, 10 or 11, can be directly cascaded to provide the optimum response without having either a differentiator for compensating for the response of the optical receiver or an integrator for complementing the response of the sine filter.

Fig. 12 illustrates in a block diagram an optical receiver arrangement which comprises such cascaded circuits. In Fig. 12, an optical receiver 42, which is as described above with reference to Fig. 6, 7, or 8, has its output coupled directly to a filter 44, which is as described above with reference to Fig. 9, 10, or 11. The output  $V_{out}$  of the filter 44 is coupled via a low-pass filter 46 to a digital comparator 48, from which a recovered binary digital signal is derived in known manner. The low-pass filter 46, which can have a cut-off frequency approximately equal to the bit rate of the digital signal, e.g. 600MHz for a digital signal having a bit rate of 600Mb/s, serves to restrict noise levels to those contributed substantially only within the first lobe of the sine filter of Fig. 9, 10, or 11, as described above. The design of this low-pass filter 46 is not

particularly critical, and it can alternatively be between the optical receiver 42 and the filter 44 or incorporated within either of these circuits. The optical receiver arrangement may further include additional amplification and/or a.g.c. stages which may be provided in any desired location between the output of the optical receiver 42 and the input of the comparator 48.

Fig. 13 illustrates an optical receiver in accordance with another embodiment of the invention, which can be used in place of the optical receiver of Fig. 6, 7, or 8, with the sine filter of Fig. 9, 10, or 11 and the optical receiver arrangement of Fig. 12. As illustrated in Fig. 13, this optical receiver is substantially the same as that of Fig. 6 except that the photodiode 10 is biased in the conventional manner via the load resistor 16 as in the prior art of Fig. 2.

Fig. 14 illustrates a further form of optical receiver in which the integrating function of the receivers of Figs. 6 to 8 and 13 is avoided for lower frequency spectral components which could otherwise limit the dynamic range of the receiver. Such lower frequency spectral components can in particular arise from the so-called digital sum variation or DSV of the data stream which modulates the received optical signal. In the SONET (synchronous optical network) standard, which relies on scrambling rather than line coding to moderate the DSV, there is a possibility of significant DSV build-up which could adversely affect the operation of a purely integrating receiver as in Figs. 6 to 8 and 13.

Accordingly, in the receiver of Fig. 14 the capacitor 28 constituting the transimpedance element has connected in parallel with it a resistor 50; accordingly the d.c. blocking capacitor is connected between these components 28 and 50 and the output of the amplifier 13, as described above with reference to Fig. 3. Although the photodiode 10 can be biased as described above, in Fig. 14 a further resistor 52 is connected between the resistor 50 and a supply voltage  $V_-$  to complete a d.c. bias path for the photodiode 10.

The resistance of the resistor 50 is selected to be sufficiently high so as not significantly to increase the receiver thermal noise, and low enough to produce with the capacitance of the capacitor 28 a time constant which is low enough to alleviate the

DSV-related dynamic range. In particular, this time constant is substantially greater than the bit period of the modulating data for which the receiver is intended to operate.

For example, for a bit rate of 600Mb/s (bit period of 1.67ns),  
5 the capacitance of the capacitor 28 may be 0.4pF and the resistance of the resistor 50 may be 10k $\Omega$ , giving a time constant of 4ns. The receiver output level change due to a large DSV is then limited to less than 5 times that due to a single one-zero data transition.

It should be noted that this resistive by-passing of the  
10 integrating capacitor 28 is quite different and distinct in operation and effect from known optical receivers, such as illustrated in Fig. 2, in which the transimpedance resistor 14 may have a stabilizing capacitor (not shown) connected in parallel with it. In such a prior art receiver the resistance of the resistor 14 and the capacitance of  
15 the stabilizing capacitor would define a time constant significantly less than the bit period, typically about 0.4ns for the bit rate of 600Mb/s discussed above. Such prior art receivers have a gain which is constant with increasing frequency up to a predetermined 3dB cut-off frequency, and then rolls off at a rate of 12dB/octave at higher  
20 frequencies. In contrast, the receiver of Fig. 14 has a constant gain at low frequencies, then an integrating response with a gain decreasing with increasing frequency at a rate of 6dB/octave at operating frequencies including the intended bit rate (e.g. 600Mb/s), with a subsequent higher-frequency roll-off at 12dB/octave. The  
25 integrating response part of the gain-frequency characteristic of the receiver of Fig. 14 is not present in the prior art.

In order to compensate for this modified response in the receiver of Fig. 14, a compensating circuit is provided as illustrated for example in Fig. 15. The compensating circuit comprises an  
30 inverting amplifier 54 with an input resistor 56 and a negative feedback path from its output to its inverting input comprising a series-connected resistor 58 and capacitor 60. The time constant defined by the resistance of the resistor 58 multiplied by the capacitance of the capacitor 60 is selected to be the same as the time  
35 constant (4ns as described above) in the optical receiver, so that the compensating circuit's integrating response at lower frequencies and



flat response at higher frequencies exactly compensates for the modified characteristics of the receiver.

As illustrated in Fig. 16, the sine filter 44 of Fig. 9, 10, or 11 is provided between the optical receiver 62 of Fig. 14 and the compensating circuit 64 of Fig. 15 in order to remove the lower frequency spectral components which would otherwise re-introduce the large level excursions induced by a large DSV when passed through the compensating circuit.

Although embodiments of the invention have been described above in detail, it should be appreciated that numerous modifications, adaptations, and variations may be made thereto without departing from the scope of the invention as defined in the claims.

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## WHAT IS CLAIMED IS:

1. An optical receiver comprising:  
a transimpedance amplifier comprising an amplifier having an  
5 inverting input, an output, and a transimpedance element coupled  
therebetween;  
a photodiode and a d.c. load impedance therefor connected in  
series therewith;  
means for reverse biasing the photodiode via the d.c. load  
10 impedance; and  
coupling means coupling a junction between the photodiode and  
the d.c. load impedance to said inverting input;  
characterized in that the transimpedance element is capacitive.
- 15 2. An optical receiver as claimed in claim 1, for receiving  
an optical signal which is modulated with a digital signal having a  
predetermined bit period, characterized in that the transimpedance  
element comprises a capacitance with a resistance connected in  
parallel therewith, the capacitance and resistance determining a time  
20 constant which is substantially greater than the predetermined bit  
period.
3. An optical receiver as claimed in claim 2 characterized  
by:  
25 filtering means having an input coupled to the output of the  
transimpedance amplifier, the filtering means having a gain which  
increases with increasing frequency; and  
compensating means having an input coupled to an output of the  
filtering means, the compensating means including a negative feedback  
30 path comprising a resistor and a capacitor connected in series and  
determining a time constant which is substantially the same as said  
time constant determined by the capacitance and resistance of the  
transimpedance element.
- 35 4. An optical receiver as claimed in claim 3 characterized by  
a low-pass filter coupled in series with the filtering means.

5. An optical receiver as claimed in claim 3 characterized in that the filtering means comprises a bipolar transistor having a base coupled to the output of the transimpedance amplifier, a collector from which an output signal is derived, and an emitter; an emitter impedance; and a transmission line having a predetermined length to provide a signal propagation delay of half said predetermined bit period, one end of the transmission line being coupled via the emitter impedance to the emitter and the other end of the transmission line being an open circuit, the emitter impedance being matched to a characteristic impedance of the transmission line.

6. An optical receiver as claimed in any of claims 2 to 5 characterized in that the d.c. load impedance comprises said resistance of the transimpedance element in series with a further resistance coupled to a supply voltage rail.

7. An optical receiver as claimed in claim 1 wherein the photodiode is coupled between the input and the output of the amplifier, the capacitive transimpedance element comprising a capacitance of the photodiode.

8. An optical receiver as claimed in claim 7 characterized by a potential divider coupled to the output of the amplifier, wherein the photodiode is coupled to a tapping point of the potential divider and thereby to the output of the amplifier.

9. An optical receiver as claimed in claim 8 characterized in that the potential divider comprises a capacitive potential divider.

10. An optical receiver as claimed in any of claims 1 to 5 or 7 to 9 characterized in that the d.c. load impedance comprises a forward biased semiconductor diode.

11. An optical receiver as claimed in claim 10 characterized by signal compressing means a.c. coupled between the output of the transimpedance amplifier and a terminal of the semiconductor diode remote from said junction.

12. An optical receiver as claimed in claim 11 characterized in that the signal compressing means comprises two diodes connected in parallel with one another with opposite polarities.

5 13. An optical receiver as claimed in claim 1, 7, 8, or 9 characterized by filtering means having an input coupled to the output of the transimpedance amplifier and having a gain which increases with increasing frequency.

10 14. An optical receiver as claimed in claim 13 characterized in that the filtering means comprises a bipolar transistor having a base coupled to the output of the transimpedance amplifier, a collector for producing a filtered output signal, and an emitter; an open circuit transmission line having a characteristic impedance and a  
15 predetermined length; and an emitter impedance matched to the characteristic impedance coupling the transmission line to the emitter.

15. An optical receiver comprising:  
20 a transimpedance amplifier comprising an amplifier having an inverting input, an output, and a transimpedance element coupled therebetween;  
a photodiode and a d.c. load impedance therefor connected in series therewith;  
25 means for reverse biasing the photodiode via the d.c. load impedance; and  
coupling means coupling a junction between the photodiode and the d.c. load impedance to said inverting input;  
characterized in that the d.c. load impedance comprises a  
30 forward biased semiconductor diode.

16. An optical receiver as claimed in claim 15 characterized in that the transimpedance element is constituted by a capacitance of the photodiode.

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17. An optical receiver as claimed in claim 15 characterized in that the d.c. load impedance includes an impedance coupled in

series with the semiconductor diode on the side thereof remote from the photodiode.

18. An optical receiver as claimed in claim 17 characterized  
5 by including signal compressing means a.c. coupled between said output and a junction between the semiconductor diode and said impedance.

19. An optical receiver as claimed in claim 18 characterized  
in that the signal compressing means comprises two diodes connected in  
10 parallel with one another with opposite polarities.

20. An optical receiver as claimed in claim 15 characterized  
in that the transimpedance element comprises a capacitance.

15 21. An optical receiver as claimed in claim 20 characterized  
by filtering means having an input coupled to the output of said  
amplifier and having a gain which increases with increasing frequency.

22. An optical receiver as claimed in claim 21 characterized  
20 in that the filtering means comprises a bipolar transistor having a  
base coupled to the output of said amplifier, a collector from which  
an output signal is derived, and an emitter; an emitter impedance; and  
a transmission line having a predetermined length, one end of the  
transmission line being coupled via the emitter impedance to the  
25 emitter and the other end of the transmission line being an open  
circuit, the emitter impedance being matched to a characteristic  
impedance of the transmission line.

23. An optical receiver as claimed in claim 21 or 22  
30 characterized by including a low-pass filter coupled in series with  
the filtering means.

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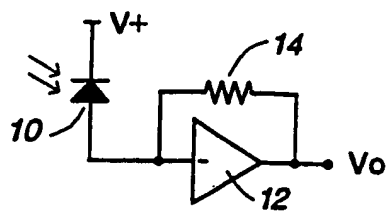


Fig. 1

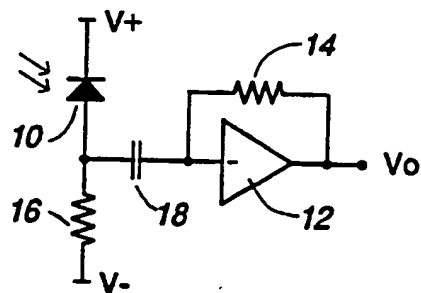


Fig. 2

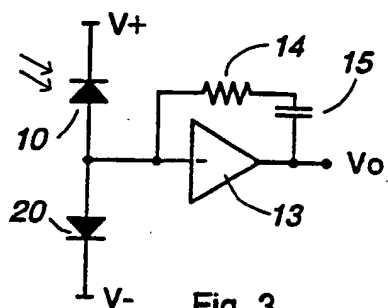


Fig. 3

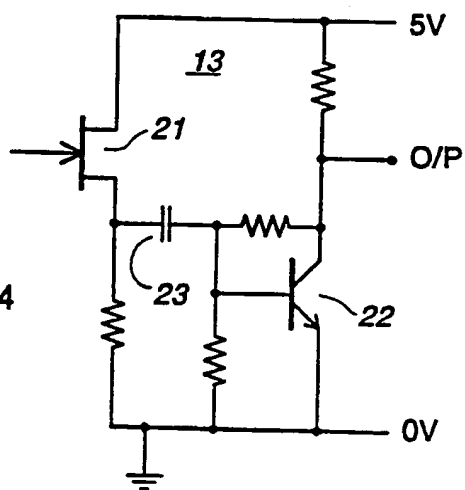


Fig. 4

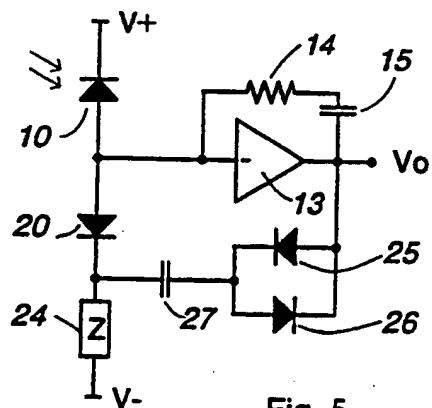


Fig. 5

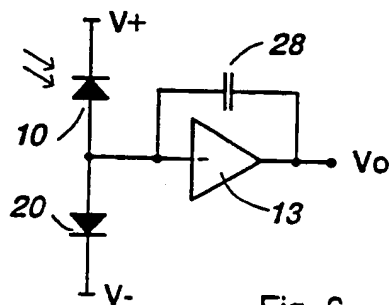
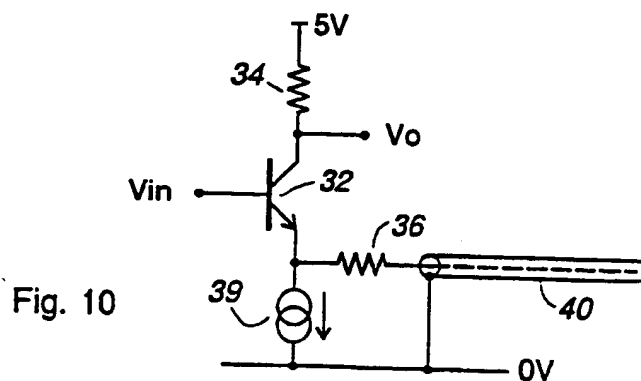
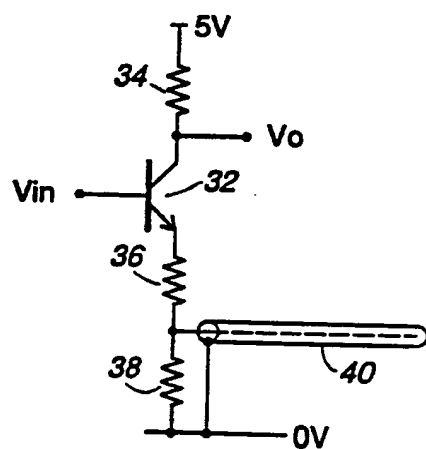
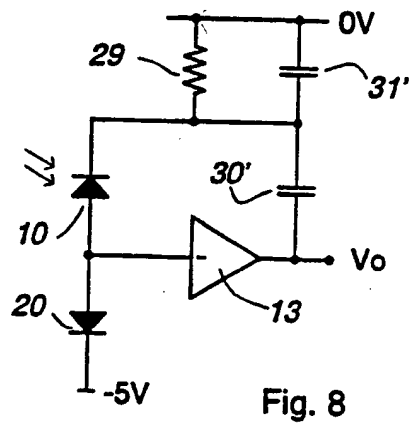
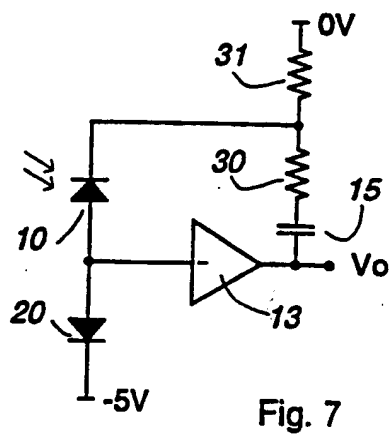


Fig. 6

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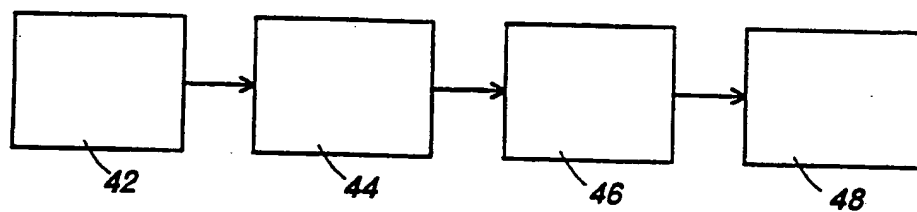
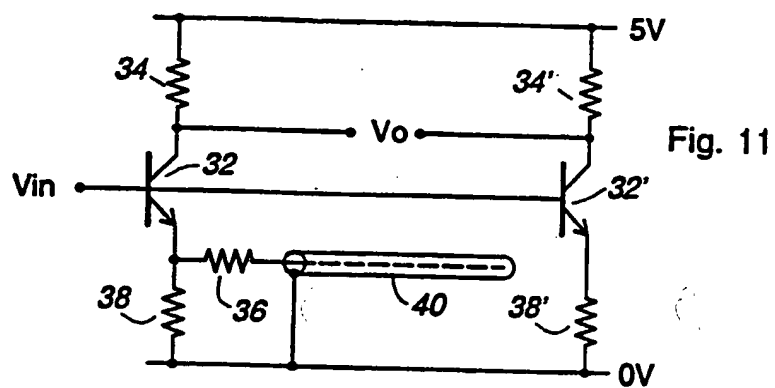


Fig. 12

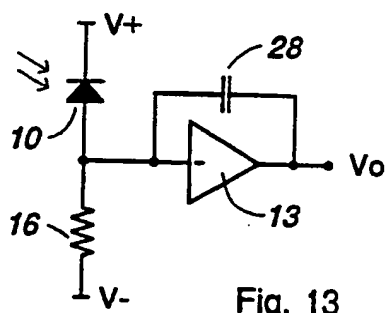


Fig. 13



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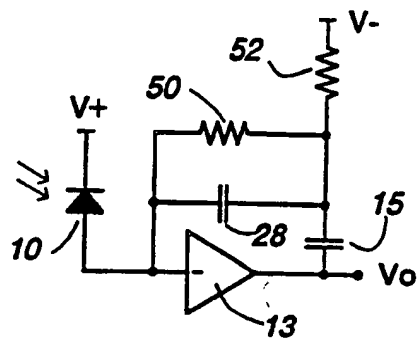


Fig. 14

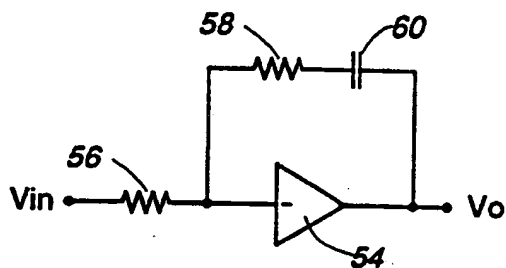


Fig. 15

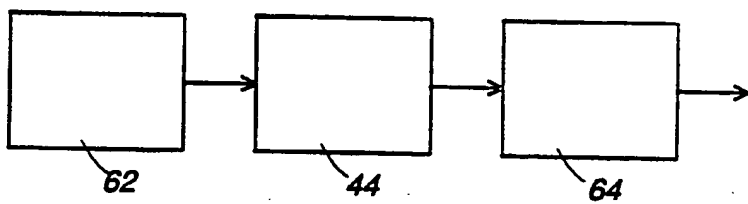



Fig. 16

## INTERNATIONAL SEARCH REPORT

International Application No.

PCT/CA 90/00117

<b>I. CLASSIFICATION OF SUBJECT MATTER</b> (If several classification symbols apply, indicate all) <sup>6</sup>		
According to International Patent Classification (IPC) or to both National Classification and IPC:		
Int.Cl. 5      H03F3/08 :      H04B10/14		
<b>II. FIELDS SEARCHED</b>		
Minimum Documentation Searched <sup>7</sup>		
Classification System	Classification Symbols	
Int.Cl. 5	H03F :      H04B	
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched <sup>8</sup>		
<b>III. DOCUMENTS CONSIDERED TO BE RELEVANT<sup>9</sup></b>		
Category <sup>11</sup>	Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>13</sup>
X	ELECTRONICS LETTERS. vol. 24, no. 17, 18 August 1988, FNAGF GR pages 1061 - 1062; N.OHKAWA: "20 GHZ Bandwidth Low-Noise HEMT Preamplifier for Optical Receivers" see page 1061; figures 1a, 1b.	1, 2
A	see page 1061; figures 1a, 1b	20
A	US,A,4743856 (J.M.KEATING) 10 May 1988 see column 2, line 28 - column 3, line 12; figure 2	1-4, 23
A	TELECOMMUNICATIONS AND RADIO ENGINEERING. vol. 41/42, no. 4, April 1987, WASHINGTON US pages 130 - 132; R.M. SHIMOV, et al.: "A High-Sensitivity Photoamplifier" see figures 2-4	1-3, 13, 21
<p><sup>10</sup> Special categories of cited documents:</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"I" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> <p>"1" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"V" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"X" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"X" document member of the same patent family</p>		
<b>IV. CERTIFICATION</b>		
Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	
28 JUNE 1990	16 JUL 1990	
International Searching Authority	Signature of Authorized Officer	
EUROPEAN PATENT OFFICE	TYBERGHIEN G.M. 	

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	<p>PATENT ABSTRACTS OF JAPAN vol. 12, no. 187 (E-615)(3034) 31 May 1988, &amp; JP-A-62 290205 (NEC CORP) 17 December 1987. see the whole document</p> <p>---</p>	5, 22
A	<p>DE,A,3320801 (INTERNATIONAL STANDARD ELECTRIC CORP.) 22 December 1983 see page 4, line 7 - page 5, line 7; figures 3-6</p> <p>---</p>	7, 16
A	<p>ELECTRON. vol. 31, no. 3, March 1976, ROTTERDAM NI page 138 K.H.J.ROBERS, PAoKLS.: "Licht indicator" see figure 1</p> <p>---</p>	10, 15
A	<p>PATENT ABSTRACTS OF JAPAN vol. 11, no. 41 (E-478)(2488) 06 February 1987, &amp; JP-A-61 206303 (TOSHIBA CORP.) 12 September 1986, see the whole document</p> <p>---</p>	10, 15
A	<p>DE,A,3223218 (TELEFUNKEN ELECTRONIC GMBH) 02 February 1984 see page 5, line 24 - page 6, line 26; figure 2</p> <p>---</p>	11, 12, 18, 19

**ANNEX TO THE INTERNATIONAL SEARCH REPORT  
ON INTERNATIONAL PATENT APPLICATION NO.**

CA 9000117

SA 36038

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office (EPO) file on  
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

28/06/90

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-4743856	10-05-88	None	
DE-A-3320801	22-12-83	AU-B- 558899	12-02-87
		AU-A- 1572983	22-12-83
		GB-A, B 2122447	11-01-84
DE-A-3223218	02-02-84	None	